Creo Simulation Live Verification and Benchmark Cases

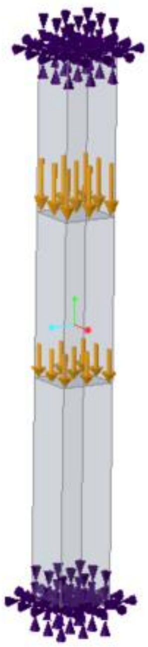
Verification Cases

1.0 Static Structural Analysis

1.1 Statically Indeterminate Reaction Force Analysis

An assembly of three prismatic bars is supported at both end faces and is axially loaded with forces F1 and F2. Force F1 is applied on the face between Parts 2 and 3 and F2 is applied on the face between Parts 1 and 2. Find reaction forces in the Y direction at the fixed supports.

Reference: S. Timoshenko, Strength of Materials, Part 1, Elementary Theory and Problems, 3rd Edition, CBS Publishers and Distributors, pg. 22 and 26



Material Properties	Geometric Properties	Loading
E = 2.9008e7 psi v = 0.3 ρ = 0.28383 lbm/in3	Cross section of all parts = 1" x 1" Length of Part 1 = 4" Length of Part 2 = 3" Length of Part 3 = 3"	Force F1 = -1000 (Y direction) Force F2 = -500 (Y direction)

Results Comparison for Discovery LIve (Quadro M2000M 4GB Graphics Card, Default Fidelity)

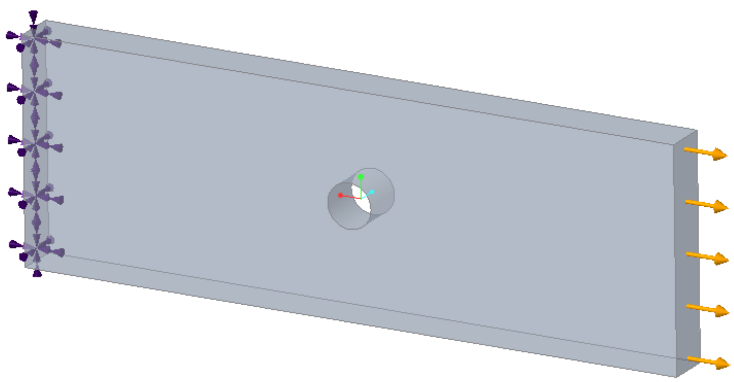
Results	Target	Simulate	Discovery Live	Simulate live	Percent Error*	Percent Difference #
Y Reaction Force at Top Fixed Support (lbf)	900	900.164	899.4	899.4	0.067	0
Y Reaction Force at Bottom Fixed Support (lbf)	600	599.836	599.6	600.6	0.1	0.167

* Percentage difference between results and target value
# Percentage difference in results from Discovery live and Simulate live

1.2 Rectangular Plate with Circular Hole Subjected to Tensile Loading

A rectangular plate with a circular hole is fixed along one of the end faces and a tensile pressure load is applied on the opposite face. Find the Maximum Normal Stress in the x direction on the cylindrical surfaces of the hole.

Reference: J. E. Shigley, Mechanical Engineering Design, McGraw-Hill, 1st Edition, 1986, Table A-23, Figure A-23-1, pg. 673

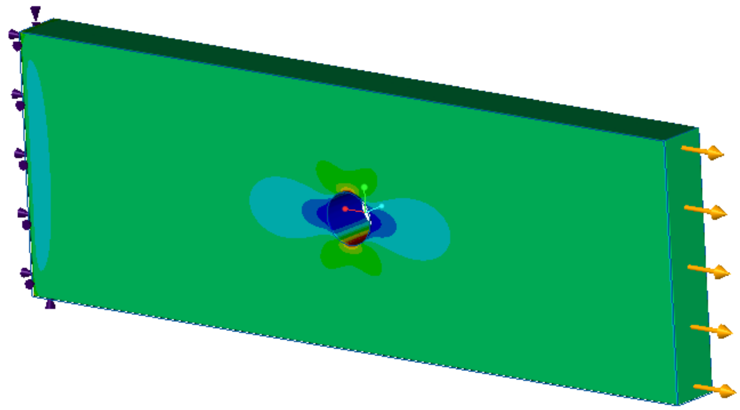


Material Properties	Geometric Properties	Loading
E = 1000 Pa v = 0.0	Length = 15 m Width = 5 m Thickness = 1 m Hole radius = 0.5 m	Pressure = -100 Pa

Results Comparison for Discovery LIve (Quadro M2000M 4GB Graphics Card, Default Fidelity)

Results	Target	Simulate	Discovery Live	Simulate live	Percent Error	Percent Difference
Maximum Normal X Stress (Pa)	312.5	313.272	296.65	281.8	9.81	4.99

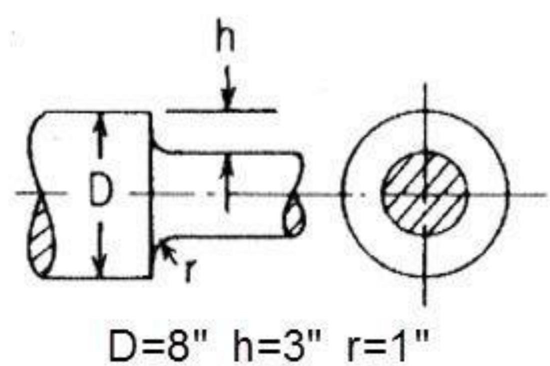
Results Comparison for Discovery LIve (Quadro M2000M 4GB Graphics Card, Maximum Fidelity)



Results	Target	Discovery Live	Simulate live	Percent Error	Percent Difference
Maximum Normal X Stress (Pa)	312.5	337.8	300	4	11.19

1.3 Stepped Shaft in Axial Tension

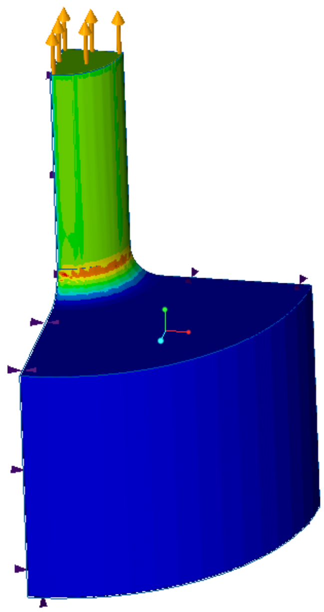
Consider a stepped shaft under an applied axial load of 1000 psi on the smaller cross section of the shaft, compute the stress concentration based on the fillet radius at the step as shown below:



Reference: Roark's Formulas for Stress and Strain, Warren C. Young and Richard G. Budynas, 2002

Material Properties	Geometric Properties	Loading
E = 2.9008e7 psi v = 0.3	D = 8 in h = 3 in r = 1 in	Pressure = -1000 psi

Results Comparison for Discovery LIve (Quadro M2000M 4GB Graphics Card, Default Fidelity)

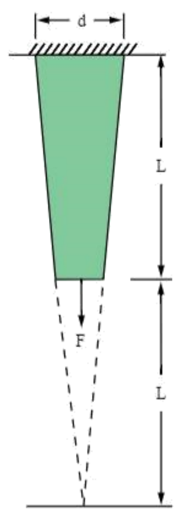


Results	**Target**	**Simulate**	**Discovery Live**	**Simulate live**	**Percent Error**	**Percent Difference**
Maximum Normal Y Stress (psi)	1376	1422.63	1497.6	1503	9.23	0.36

1.4 Elongation of a Solid Bar

A tapered aluminum alloy bar of square cross-section and length L is suspended from a ceiling. An axial load F is applied to the free end of the bar. Determine the maximum axial deflection δ in the bar and the axial stress σ_y at mid-length (Y = L/2).

Reference: C. O. Harris, Introduction to Stress Analysis, The Macmillan Co., New York, NY, 1959, pg. 237, problem 4.



Material Properties	Geometric Properties	Loading
E = 10.4e6 psi v = 0.3	L = 10 in d = 2 in	F = 10000 lbf

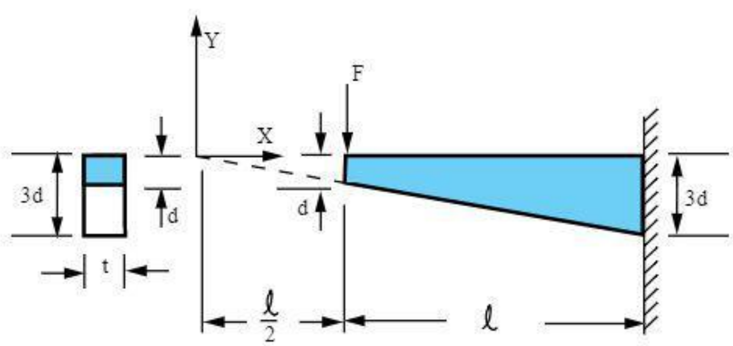
Results Comparison for Discovery Live (Quadro M2000M 4GB Graphics Card, Default Fidelity)

Results	Target	Simulate	Discovery Live	Simulate live	Percent Error	Percent Difference
Directional Deformation Y (in)	0.0048077	0.0048156	0.004807	0.004807	0.015	0
Normal Stress Y at L/2 (psi)	4444	4439.45	4432			

1.5 Laterally Loaded Tapered Beam

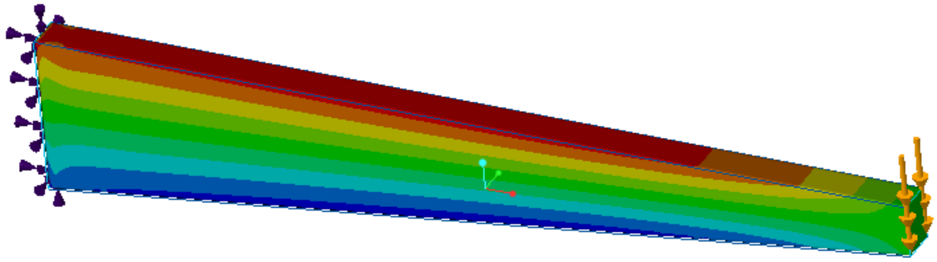
A cantilever beam of thickness t and length l has a depth which tapers uniformly from d at the tip to 3d at the wall. It is loaded by a force F at the tip, as shown. Find the maximum bending stress at the mid-length and the fixed end of the beam.

Reference: S. H. Crandall, N. C. Dahl, *An Introduction to the Mechanics of Solids*, McGraw-Hill Book Co., Inc., New York, NY, 1959, pg. 342, problem 7.18.



Material Properties	Geometric Properties	Loading
E = 30e6 psi v = 0.0	l = 50 in d = 3 in t = 2 in	F = 4000 lbf

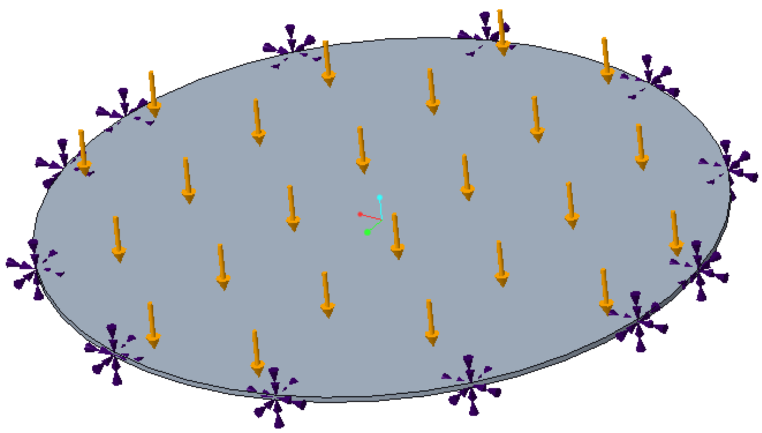
Results Comparison for Discovery Live (Quadro M2000M 4GB Graphics Card, Default Fidelity)



Results	Target	Discovery Live	Simulate live	Percent Error	Percent Difference
Mid-Length Stress (psi)	8333	8229.5	-		
Fixed End Stress (psi)	7407	-	-		

1.6 Circular Plate under Uniform Pressure

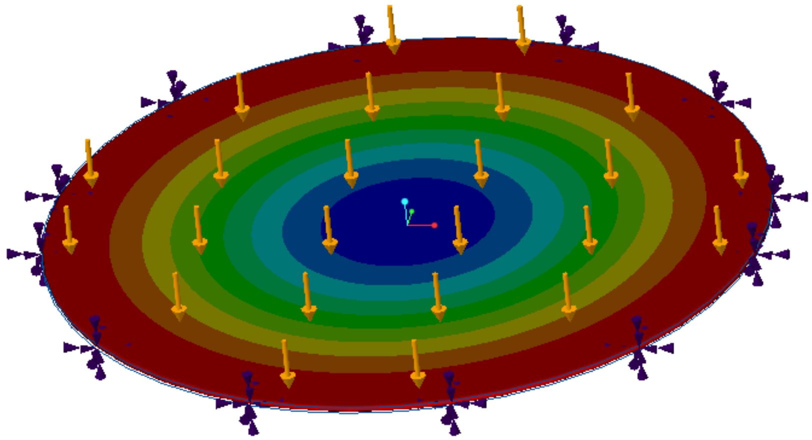
Consider a circular plate with fixed edges under a uniformly distributed pressure load. Find the maximum deflection and bending stress in the center of the plate.



Reference: R. J. Roark, W. C. Young, *Formulas for Stress and Strain*, McGraw-Hill Book Co., Inc., New York, NY, 1975, Table 24.

Material Properties	Geometric Properties	Loading
E = 30e6 psi v = 0.3	Diameter = 30 in Thickness = 0.25 in	P = 3 psi

Results Comparison for Discovery Live (Quadro M200M 4GB Graphics Card, Maximum Fidelity)



Results	Target	Simulate	Discovery Live	Simulate live	Percent Error	Percent Difference
Deflection center of plate, in	0.0553	0.0549	0.0512	0.0512	7.41	0
Bending stress center of plate, psi	5265					

Results Comparison for Discovery Live (8 GB Graphics Card, Max Fidelity)

Results	Target	Discovery Live	Simulate live	Percent Error	Percent Error DL
Deflection center of plate, in	0.0553	0.0541	0.0531	3.97	1.84
Bending stress center of plate, psi	5265				

2.0 Modal Analysis

2.1 Cantilever Beam Modal Analysis

Consider a cantilever beam of length l and a width w and height h. Compute the first three bending modes and natural frequencies. (Note that the simulation results include orthogonal bending, torsional and axial modes, and the results comparison compares the first three bending modes from a closed form solution with the equivalent simulation results.)

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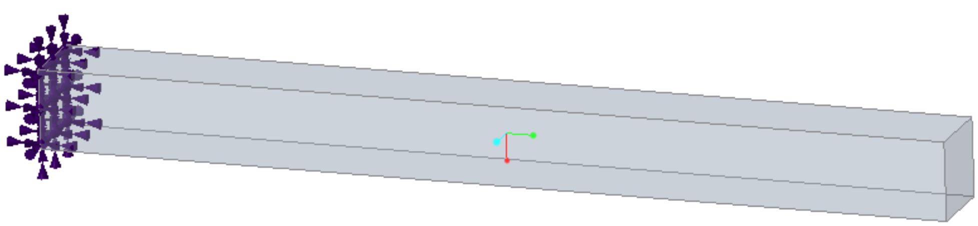
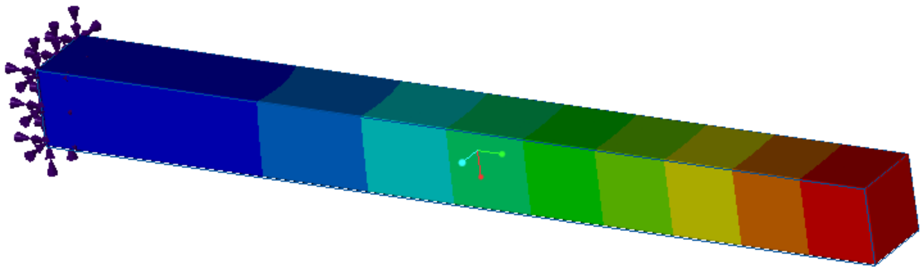


Reference: W. T. Thompson, Theory of Vibration with Applications, 2nd Edition, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1981, pg. 220

Material Properties	Geometric Properties
E = 70e9 Pa v = 0.35 ρ = 2700 kg/m^3	l = 4 m w = 0.346 m h = 0.346 m

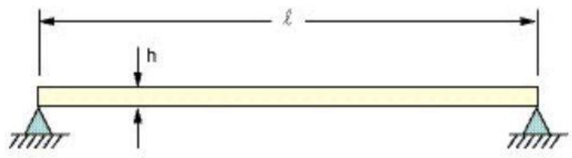
Results Comparison for Discovery Live (Quadro M200)M 4GB Graphics Card, Default Fidelity)



Results	Target	Simulate	Discovery Live	Simulate live	Percent Error	Percent Difference
Frequency Mode 1 (Hz)	17.8	17.88	17.8	17.82	0.1	0.1
Frequency Mode 3 (Hz)	111.5	110.03	108	107.98	3.2	0.02
Frequency Mode 6 (Hz)	312.1	320.22	287	288.09	7.7	0.38

2.2 Simply-Supported Beam Modal Analysis

Determine the fundamental frequency f of a simply-supported beam of length 80 in and uniform cross-section A = 4 in^2 as shown below.



Reference: W. T. Thompson, Vibration Theory and Applications, 2nd Printing, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1965, pg. 18, ex. 1.5-1

Material Properties	**Geometric Properties**
E = 3e7 psi = 0.3 ρ = 0.2836 lb/in^3	l = 80 in w = 2 in h = 2 in

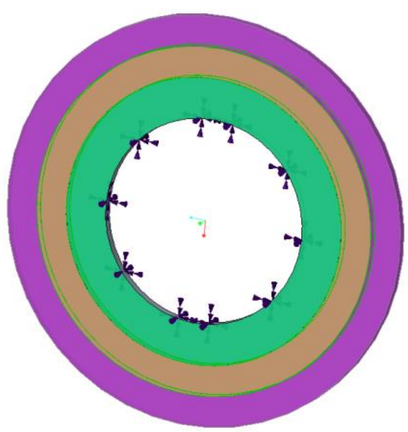
Results Comparison for Discovery Live (Quadro M2000M 4GB Graphics Card, Default Fidelity)
(Simple support approximated by constraining 0.125 in imprinted faces.)

Results	**Target**	**Simulate**	**Discovery Live**	**Simulate live**	**Percent Error**	**Percent Difference**
Frequency Mode 1 (Hz)	28.766	28.67	32.3	34.20	18.9	5.9

2.3 Modal Analysis of an Annular Plate

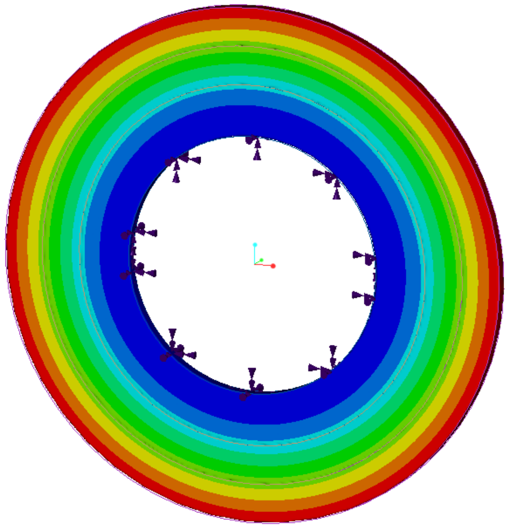
An assembly of three annular plates has cylindrical support (fixed in the radial, tangential, and axial directions) applied on the cylindrical surface of the hole. Determine the first six natural frequencies.

Reference:R. J. Blevins, Formula for Natural Frequency and Mode Shape, Van Nostrand Reinhold Company Inc., 1979, Table 11-2, Case 4, pg. 247



Material Properties	**Geometric Properties**
E = 2.9008e7 psi = 0.3 ρ = 0.28383 lb/in^3	Inner diameter of inner plate = 20" Inner diameter of middle plate = 28" Inner diameter of outer plate = 34" Outer diameter of outer plate = 40" Thickness of all plates = 1"

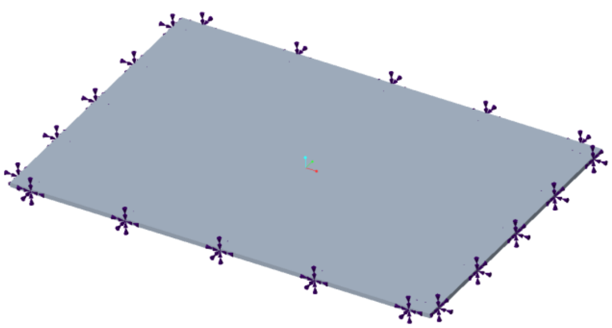
Results Comparison for Discovery Live (Quadro M2000M 4GB Graphics Card, Default Fidelity)



Results	Target	Simulate	Discovery Live	Simulate live	Percent Error	Percent Difference
Frequency Mode 1 (Hz)	310.9	310.92	321	321.5	3.41	0.16
Frequency Mode 2 (Hz)	318.1	316.37	326.6	327.2	2.86	0.18
Frequency Mode 3 (Hz)	318.1	316.50	326.7	327.2	2.86	0.15
Frequency Mode 4 (Hz)	351.6	347.80	358	358.6	1.99	0.17
Frequency Mode 5 (Hz)	351.6	347.94	358.1	358.6	1.99	0.14
Frequency Mode 6 (Hz)	442.4	436.54	446.5	447.3	1.11	0.18

2.4 Modal Analysis of a Rectangular Plate

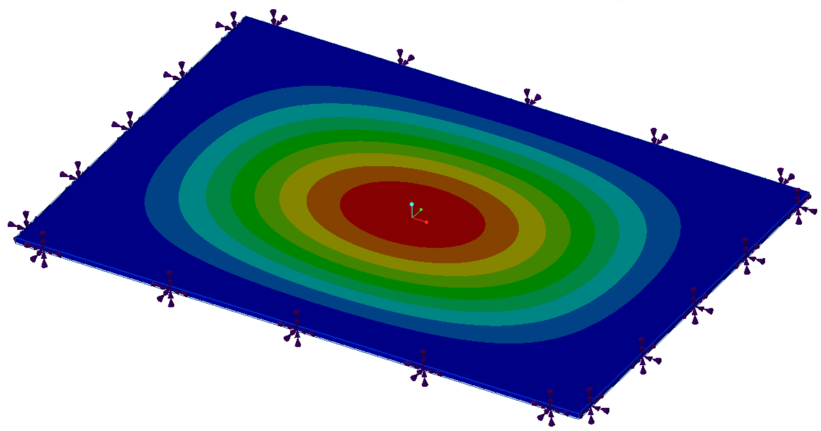
Consider a rectangular plate with fixed supports where the dimensions of the plate are length = 6 in, width = 4 in and thickness = 0.063 in. Determine the natural frequency and mode shape.



Reference:R. Blevins, Formula for Natural Frequency and Mode Shape, Van Nostrand Reinhold Company Inc., 1979, Table 11-6

Material Properties	Geometric Properties
E = 1.0e7 psi = 0.33 ρ = 0.1 lbm/in^3	Length = 6 in Width = 4 in Thickness = 0.063 in

Results Comparison for Discovery Live (Quadro M2000M 4GB Graphics Card, Default Fidelity)



Results	Target	Simulate	Discovery Live	Simulate live	Percent Error	Percent Difference
Frequency Mode 1 (Hz)	1016	1019.35	1075.7	1075.7	5.88	0.00

3.0 Thermal Analysis

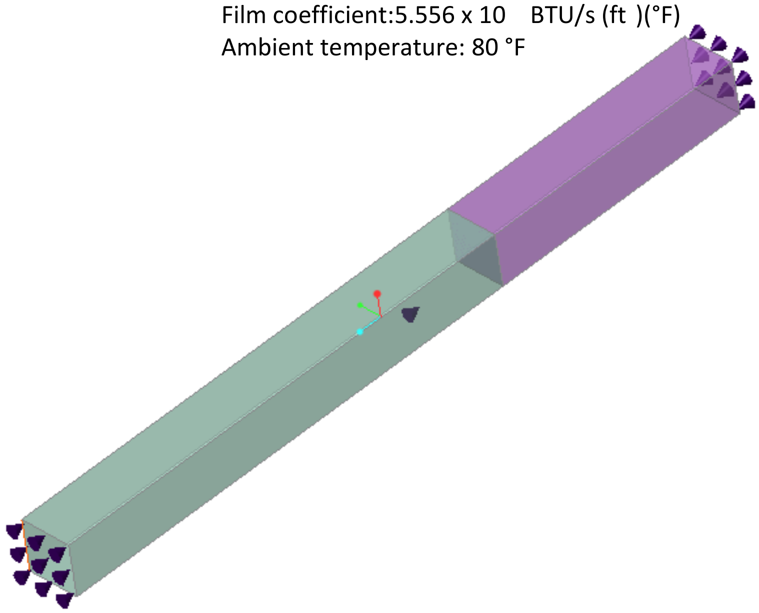
3.1 Heat Transfer in a Composite Wall

A furnace wall consists of two layers: fire brick and insulating brick. The temperature inside the furnace is 3000°F (T_f) and the inner surface convection coefficient is 3.333 x 10^{-3} BTU/s ft^2 °F (h_f).
The ambient temperature is 80°F (T_a) and the outer surface convection coefficient is 5.556 x 10^{-4} BTU/s ft^2 °F (h_a). Find the temperature distribution in the composite wall.

Reference: F. Kreith, *Principles of Heat Transfer*, Harper and Row Publisher, 3rd Edition, 1976, Example 2-5, pg. 39

Convection:

Film coefficient:5.556 x 10^{-4} BTU/s (ft^2)(°F)
Ambient temperature: 80 °F

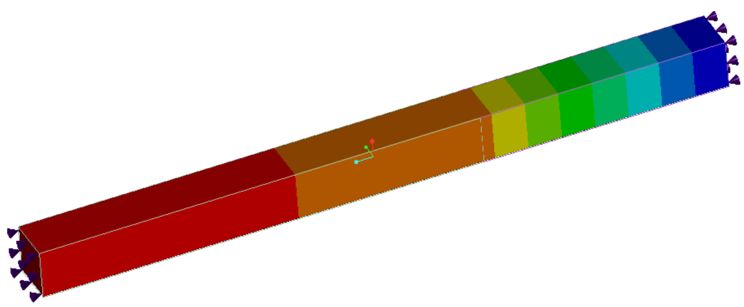


Convection:

Film coefficient:3.333 x 10^{-3} BTU/s (ft^2)(°F)
Ambient temperature: 3000 °F

Material Properties	**Geometric Properties**
Fire brick: k = 2.222 x 10^{-4} BTU/s ft °F Insulation: k = 2.778 x 10^{-5}BTU/s ft °F	Cross-section = 1" x 1" Fire brick thickness = 9" Insulating wall thickness = 5"

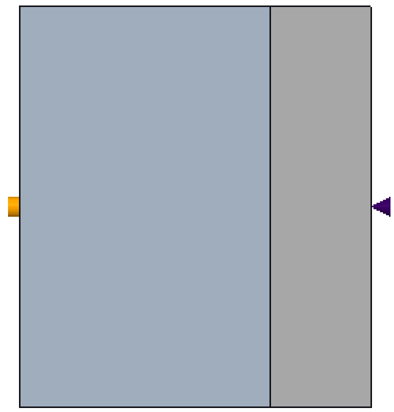
Results Comparison for Discovery Live (Quadro M2000M 4GB Graphics Card, Default Fidelity)



Results	**Target**	**Simulate**	**Discovery Live**	**Simulate live**	**Percent Error**	**Percent Difference**
Minimum Temperature (°F)	336	336.64	326	333	0.89	2.15
Maximum Temperature (°F)	2957	2597.17	2964	2964	0.24	0.00

3.2 Conduction in a Composite Solid Block

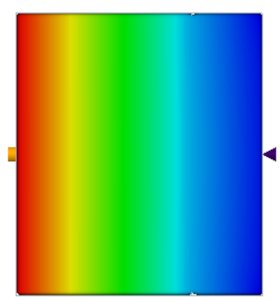
Consider heat conduction in a wall formed as composite of two materials. Material one has a uniform heat generation source equal to 6000 Watts applied to the outer surface, while material two has an outer surface exposed to convective cooling. Compute the temperature of the adiabatic surface on the left hand side of the domain.



Reference:F.P. Incropera, D.P. Dewitt. Fundamentals of Heat and Mass Transfer. 5th Edition, pg. 117, 2006.

Material Properties	**Geometric properties**	**Loading**
Material One: Conductivity = 75 W/m-K Material Two: Conductivity = 150 W/m-K	Dimensions of the block: 70 mm X 80 mm Material one = 50 mm Material two = 20 mm Thickness = 1000 mm	Left surface: Heat flow = 6000 W Right surface: HTC = 1000 W/m^2 K and fluid bulk temperature = 30 C All other surfaces are adiabatic.

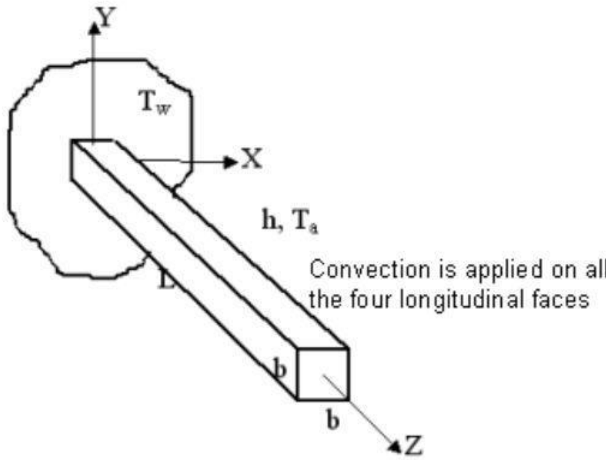
Results Comparison for Discovery Live (Quadro M2000M 4GB Graphics Card, Default Fidelity)



Results	**Target**	**Simulate**	**Discovery Live**	**Simulate live**	**Percent Error**	**Percent difference**
Temperature of the adiabatic surface on extreme left side, C	165	165	162.7	162.7	1.40	0

3.3 Heat Transfer from a Cooling Spine

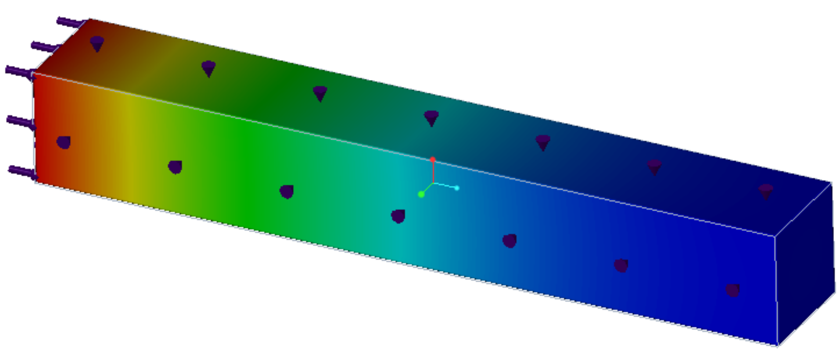
A steel cooling spine of cross-sectional area A and length L extend from a wall that is maintained at temperature T_w. The surface convection coefficient between the spine and the surrounding air is h, the air temper is T_a, and the tip of the spine is insulated.
Find the heat conducted by the spine and the temperature of the tip.



Reference: F. Kreith, "Principles of Heat Transfer", 2nd Printing, International Textbook Co., Scranton, PA, 1959, pg. 143, ex. 4-5.

Material Properties	**Geometric Properties**	**Loading**
K = 9.71×10^{-3} BTU/s-ft-°F	Cross section = 1.2 in x 1.2 in L = 8 in	T_w = 100 °F T_a = 0 °F H = 2.778×10^{-4} BTU/s-ft^2-°F

Results Comparison for Discovery Live (4GB Graphics Card, Default Fidelity)



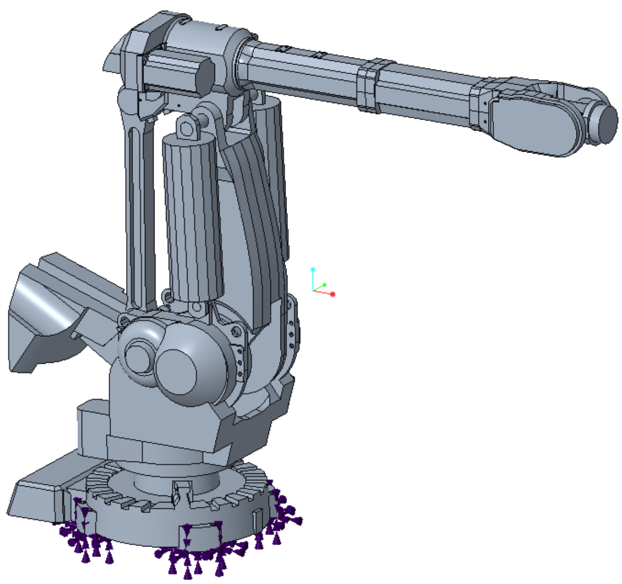
Results	**Target**	**Simulate**	**Discovery Live**	**Simulate live**	**Percent Error**	**Percent Difference**
Temperature of Tip, °F	79.0344	78.96	79.026	79.024	0.01	0.00

Benchmark Cases

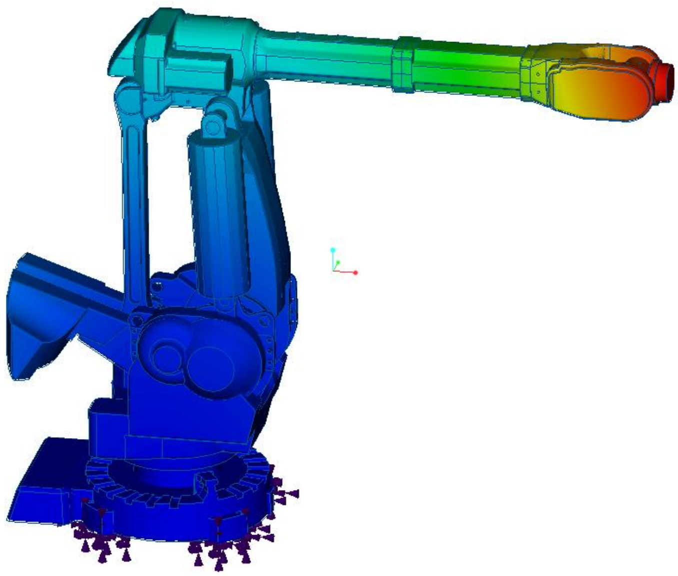
4.0 Benchmark Cases

4.1 Modal Analysis of a Robot Arm

Consider a steel robot arm assembly with a fixed base. Calculate the first three natural frequencies and mode shapes of the assembly.



Material Properties	Boundary Conditions
Young's modulus = 2e11 Pa Poisson's ratio = 0.3	Fixed support

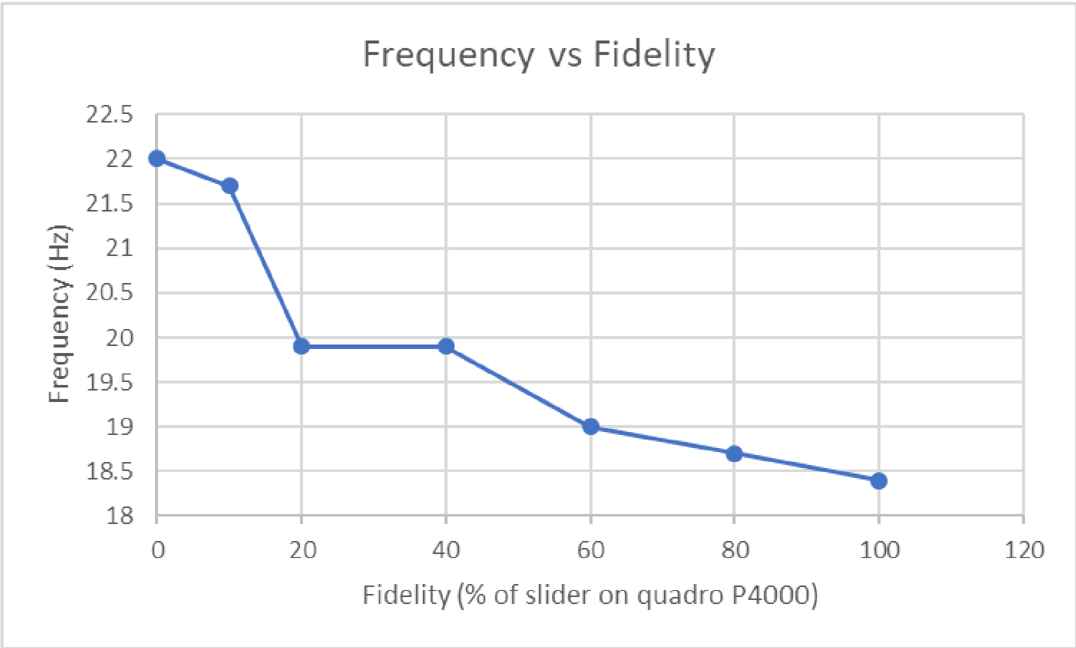


Creo Simulate Live Mode 2

Results	**Discovery Live**	**Simulate live**	**Percent difference**
Mode 1 Frequency, Hz	18.4	18.4	0.0
Mode 2 Frequency, Hz	24.2	24.2	0.0
Mode 3 Frequency, Hz	35.5	35.4	0.3

Quadro P4000, maximum fidelity

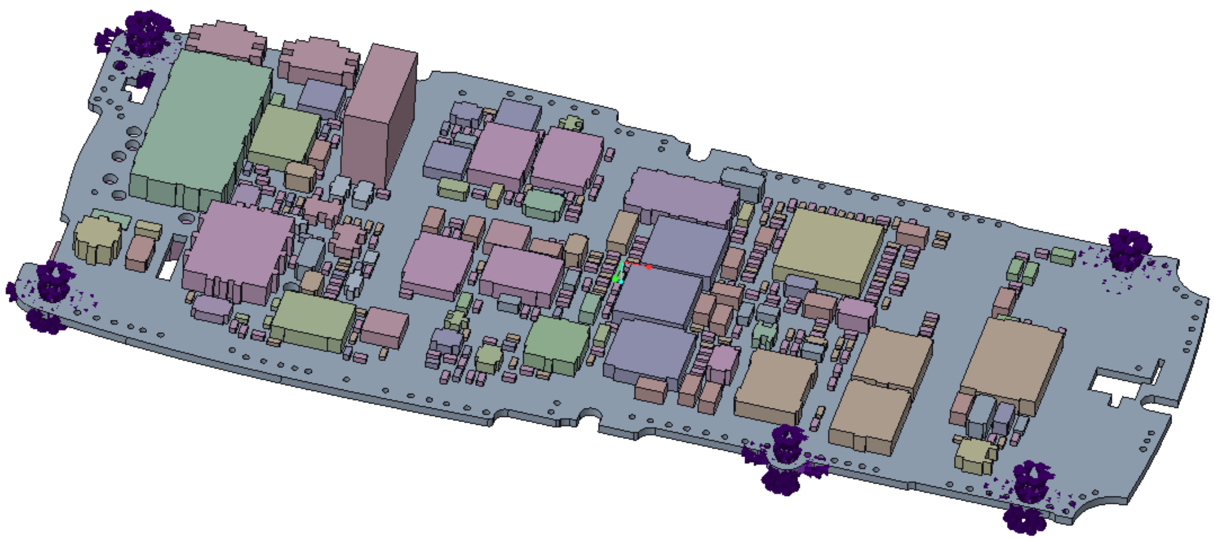
Below is the convergence of Mode 1 vs the resolution size:



Results (default fidelity P4000)	Discovery Live	Simulate live	Percent difference
Mode 1 Frequency, Hz	20.3	20.3	0.0
Mode 2 Frequency, Hz	25.7	25.7	0.0
Mode 3 Frequency, Hz	39.1	39.1	0.0

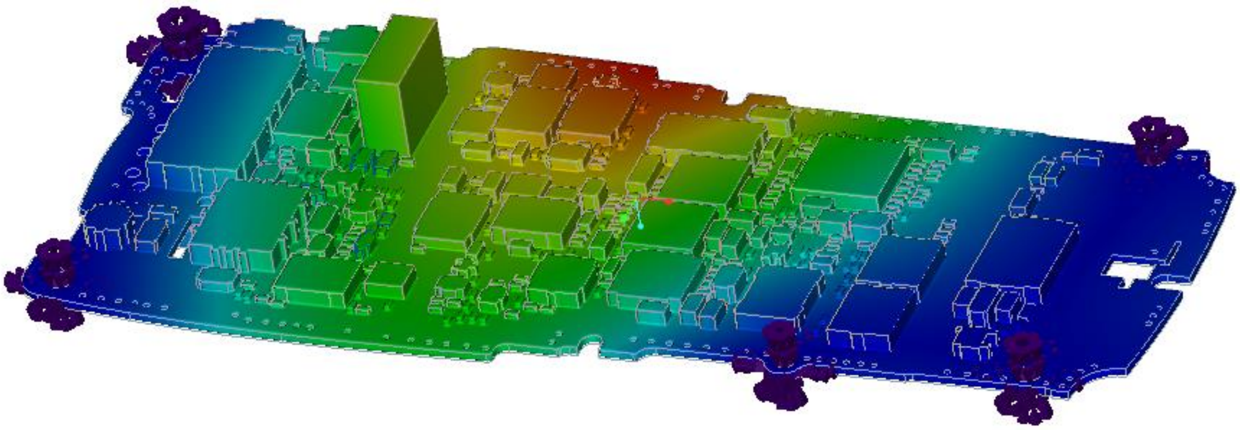
4.2 Modal Analysis of a Printed Circuit Board

Consider a printed circuit board assembly with a fixed supports. The PCB is made of FR4 and all other components are assumed to have the properties of epoxy. Calculate the first three natural frequencies and mode shapes of the printed circuit board assembly.



Printed Circuit Board Assembly

Material Properties	**Boundary Conditions**
FR4 Young's modulus = 1.1e10 Pa Density = 1900 kg/m^3 Poisson's ratio = 0.28 **Epoxy** Young's modulus = 1.1e9 Pa Density = 950 kg/m Poisson's ratio = 0.42	Fixed support on five support holes as shown

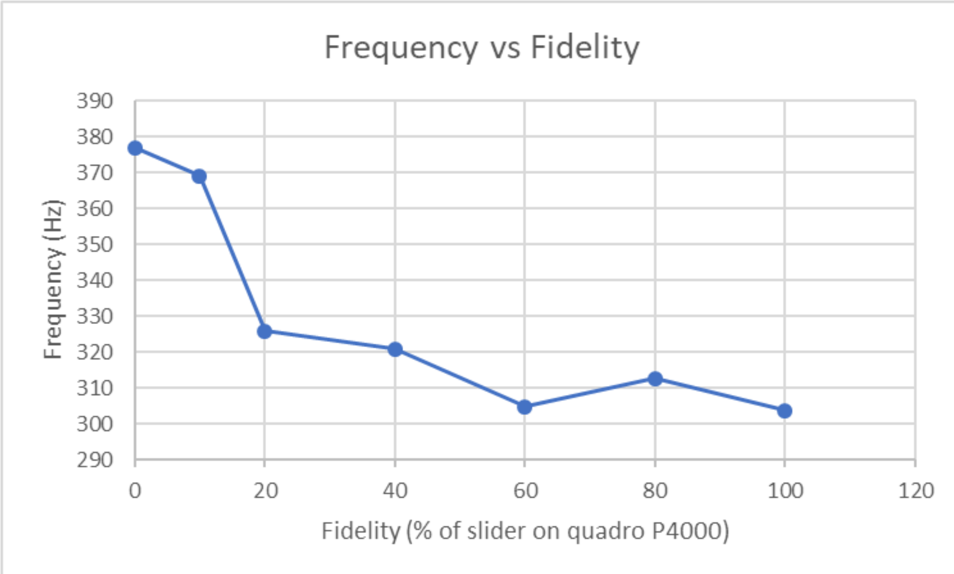


Creo Simulate Live Mode 1

Live, Quadro P4000, maximum fidelity

Results	**Discovery Live**	**Simulate live**	**Percent difference**
Mode 1 Frequency, Hz	303.8	303.848	0.02
Mode 2 Frequency, Hz	623.7	623.463	0.04
Mode 3 Frequency, Hz	836	836.091	0.01

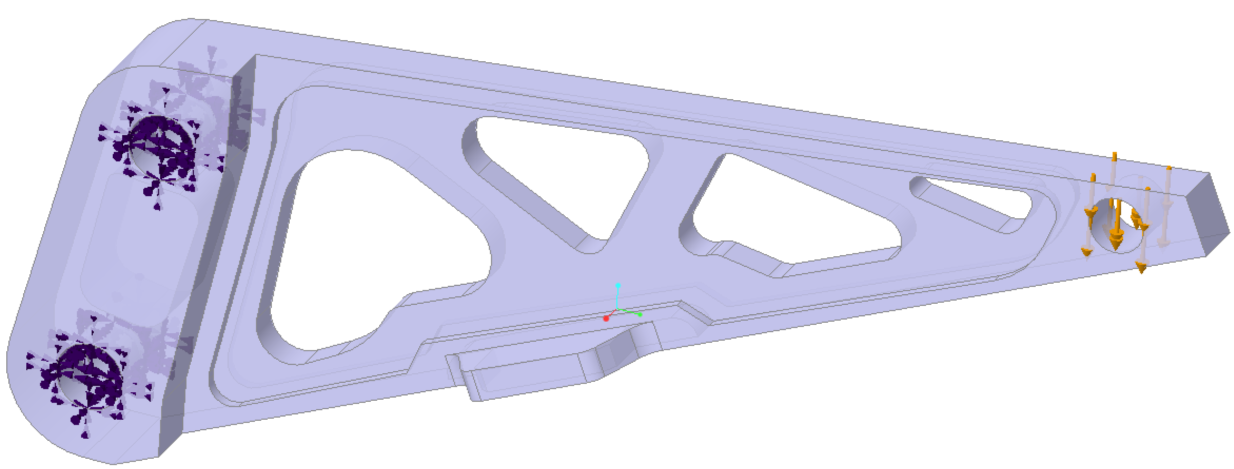
Below is the convergence of Mode 1 vs the resolution size:



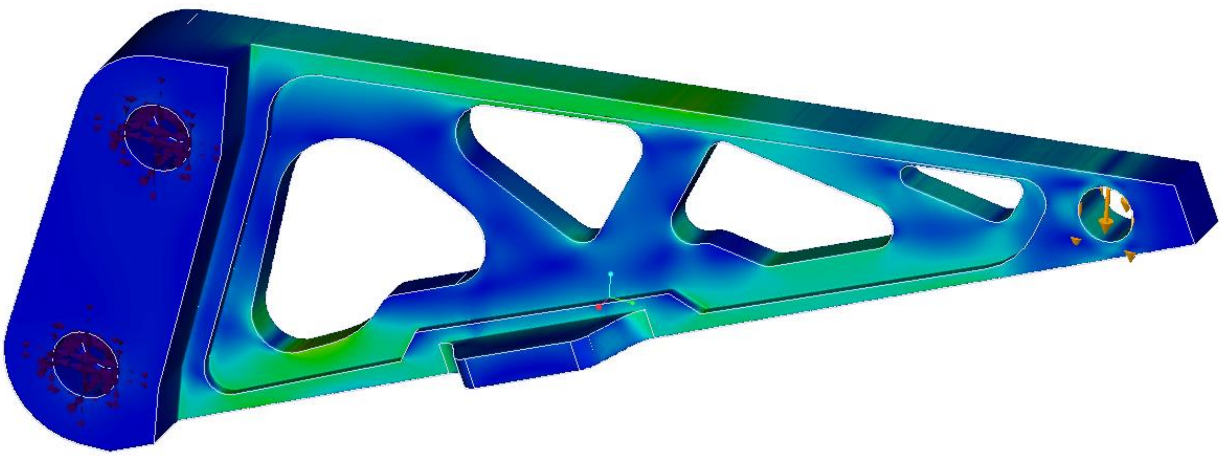
Results (default fidelity P4000)	**Discovery Live**	**Simulate live**	**Percent difference**
Mode 1 Frequency, Hz	338.7	337.6	0.30
Mode 2 Frequency, Hz	698.1	697.8	0.04
Mode 3 Frequency, Hz	940.3	938.3	0.20

4.3 Static Loading of a Bracket

Consider the static loading of an aluminum bracket. The loading consists of an applied load of 200 N and two fixed supports. Calculate the maximum tip displacement and maximum equivalent stress in the rear cut-out of the part as a function of the position of the Fidelity slider in both Discovery Live and Discovery AIM.



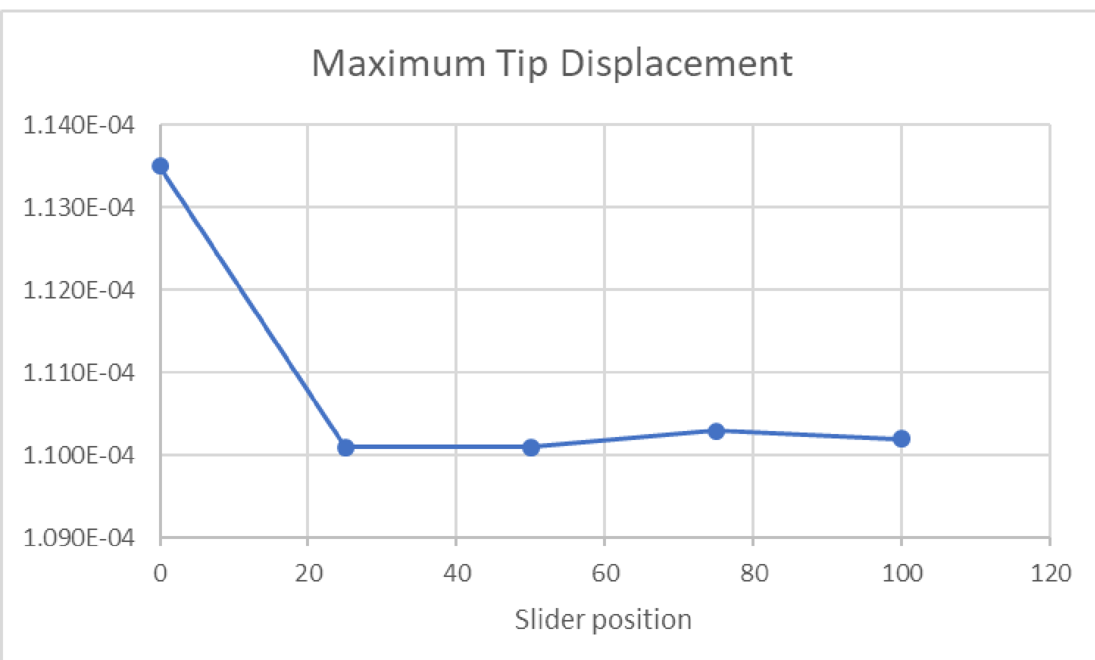
Static Loading of a Bracket



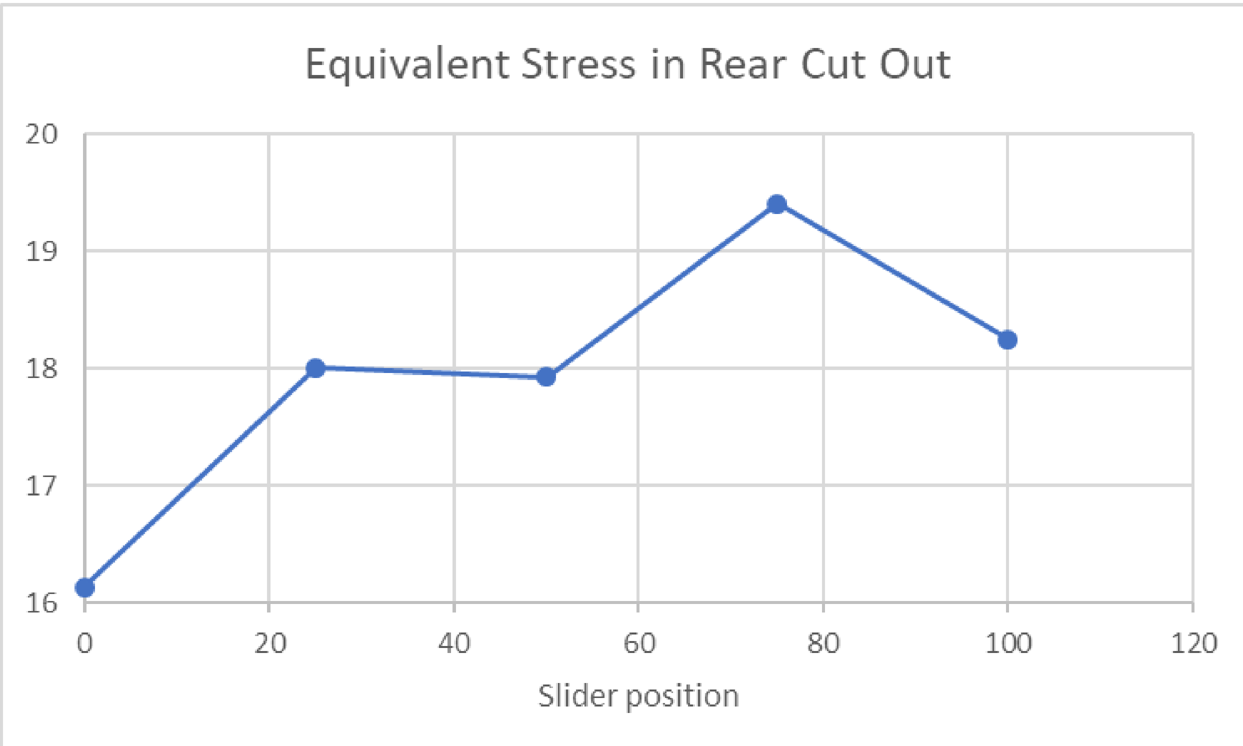
Creo Simulate Live Equivalent Stress (Max Fidelity)

Quadro P4000

Fidelity Slider Position (Percentage)	Discovery Live Displacement m	Simulate Live Displacement m	Percent difference	Percent Error Simulate Live 100% Fidelity
0	1.135E-04	1.107E-04	0.025	0.006
25	1.101E-04	1.103E-04	0.001	0.001
50	1.101E-04	1.100E-04	0.001	0.001
75	1.103E-04	1.101E-04	0.002	0.000
100	1.102E-04	1.101E-04	0.001	0.000

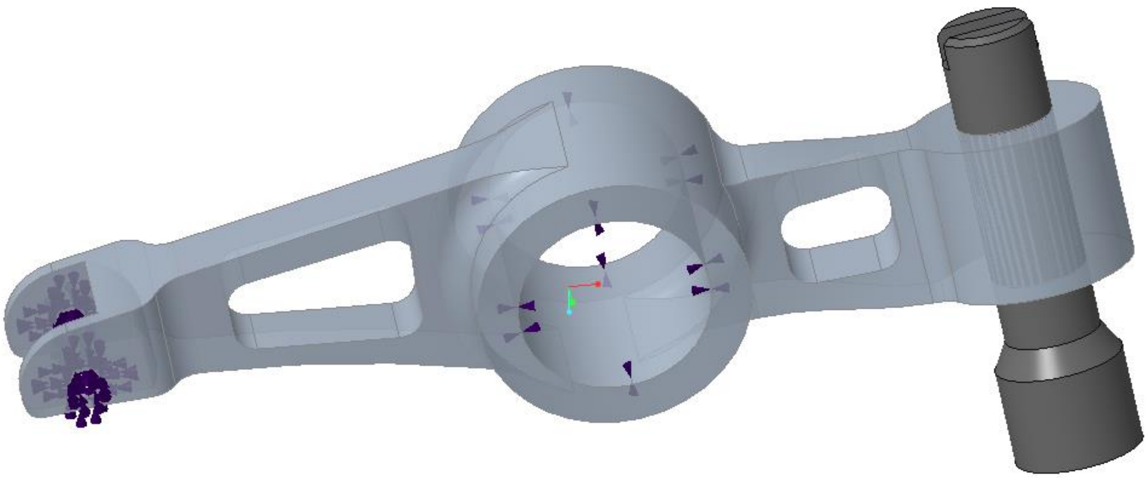


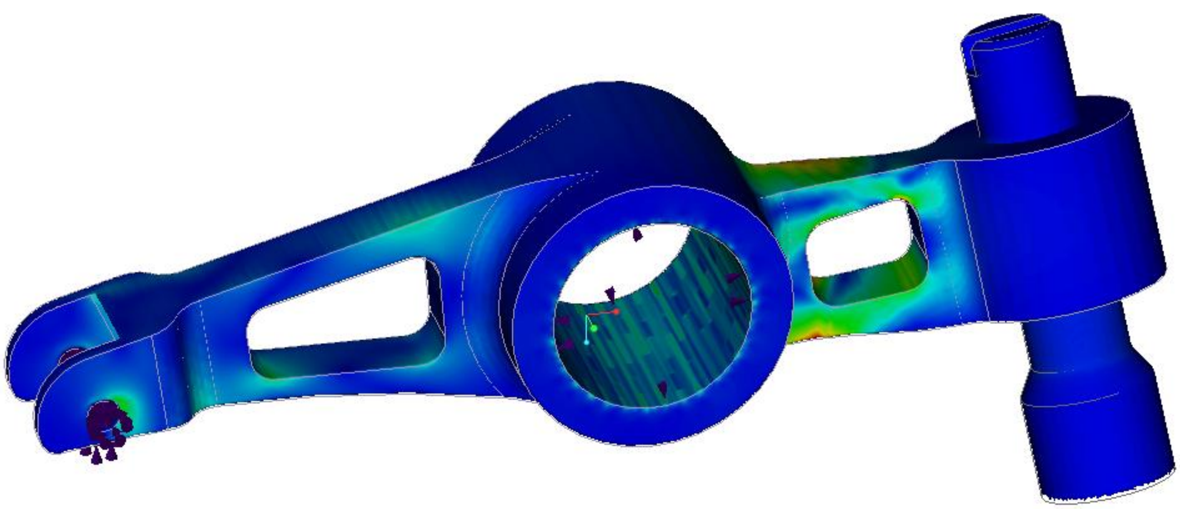
Fidelity Slider Position (Percentage)	Discovery Live Stress MPa	Simulate Live Stress MPa	Percent difference	Percent Error Simulate Live 100% Fidelity
0	16.14	16.22	0.005	0.163
25	18.01	17.25	0.044	0.110
50	17.93	17.74	0.011	0.085
75	19.41	19.16	0.013	0.011
100	18.25	19.38	0.058	0.000



4.4 Static Loading of a Rocker Arm Assembly

Consider the static loading of a rocker arm assembly with variable fillet radii. The loading consists of an applied load of 600 N, a frictionless and a fixed support. Calculate the maximum equivalent stress.





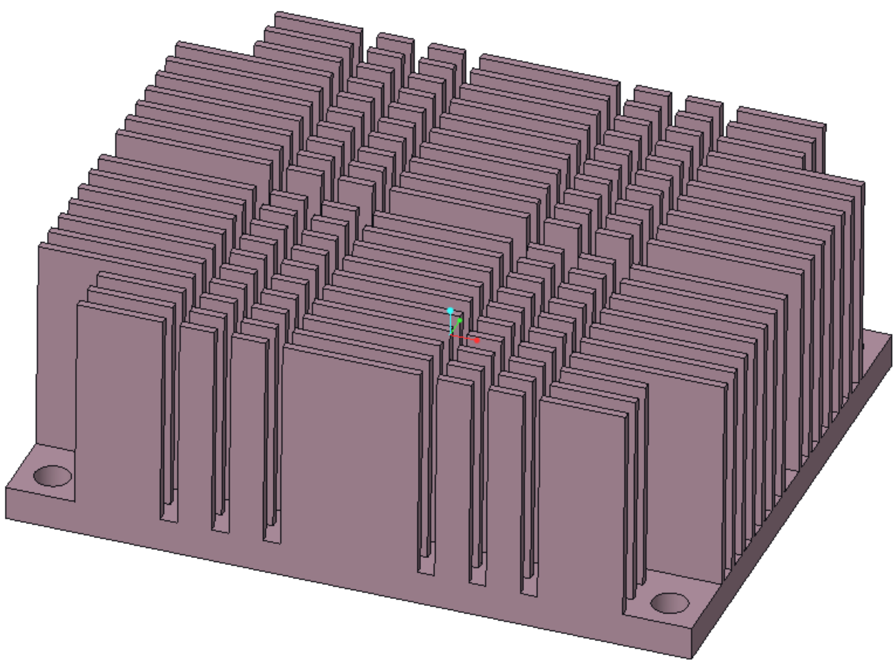
Creo Simulate Live Equivalent Stress, Radii = 3 mm

Quadro P4000, Maximum Fidelity

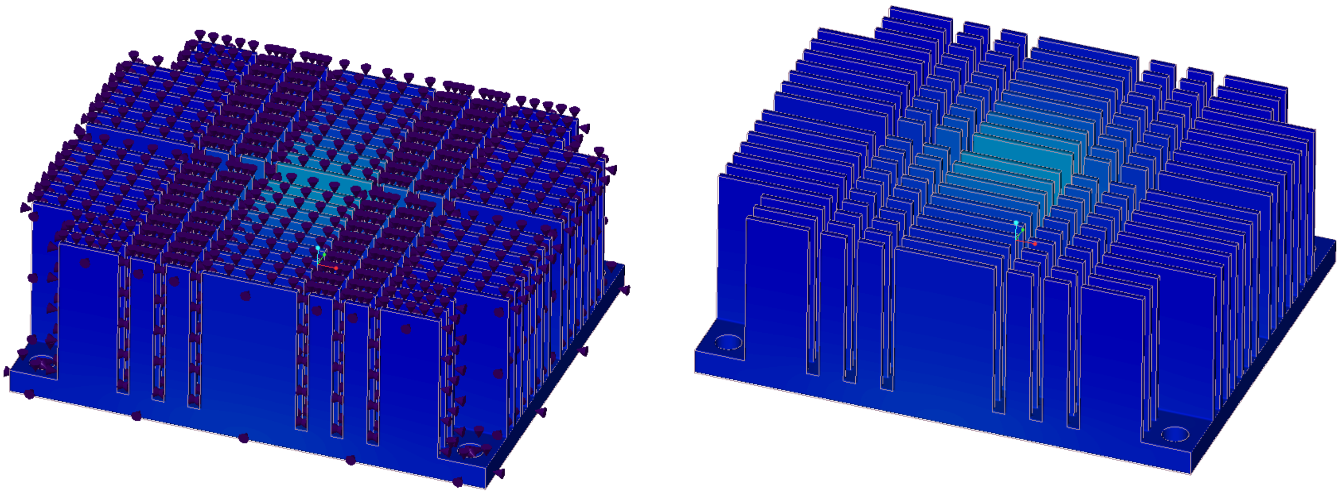
Discovery Live Stress MPa	Simulate Live Stress MPa	Percent difference
132.3	130.04	1.7

4.5 Heat Transfer in a Package/Heat Sink Assembly

Consider the steady-state heat transfer of an aluminum heat sink, thermal interface layer and package assembly. The package generates 5 Watts of power and the outer surfaces of the heat sink have a convection boundary condition with a heat transfer coefficient of 5 W/m^2 °C and fluid bulk temperature of 20 °C. Calculate the maximum temperature in the aluminum heat sink and the maximum temperature in the assembly for a steady-state condition.



Material Properties	Boundary Conditions
Aluminum, K = 148.62 W/m °C TIM, K = 24 W/m °C Package, K = 2 W/m °C	Package Heat Flow = 5 W Heat Transfer Coefficient = 5 W/m^2 °C Fluid Bulk Temperature = 20 °C



Live temperature in heat sink/package assembly

Live, Quadro P4000 default fidelity

Results: Default Fidelity	**Discovery Live Stress MPa**	**Simulate Live Stress MPa**	**Percent difference**
Max Temperature Heat Sink, °C	43.3	43.85	1.3
Max Temperature, °C	52.5	52.48	0.04

Results: Maximum Fidelity	**Discovery Live**	**Simulate Live**	**Percent difference**
Max Temperature Heat Sink, °C	42.908	42.45	1.1
Max Temperature, °C	52.523	51.25	2.4